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MELBOURNE, VICTORIA

AERODYNAMICS NOTE 410

A PROJECTED LARGE LOW-SPEED WIND TUNNEL TO MEET AUSTRALIAN REQUIREMENTS

by

D. A. LEMAIRE, N. MATHESON, D. H. THOMPSON

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SUMMARY

In this note, the requirement for a new Australian low-speed wind tunnel of increased capability is discussed, and a proposal is made for the form such a facility should take.

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16. *ABSTRACT*

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CONTENTS

1. INTRODUCTION

The requirement for a major new Australian low speed wind tunnel is examined in this report and the form such a facility should take is proposed.

The need to update local wind tunnel facilities has been under consideration for some time, and was endorsed when the Australian Science and Technology Council recommended in 1979 that the Department of Defence consult with relevant government authorities and with industry and formulate long term plans for "upgrading and extending facilities for research and development in aeronautics and aerospace". Further strong and specific affirmation was given in October 1980 in the report of the Independent External Review Committee on the Defence Science and Technology Organisation.

The existing low speed wind tunnel at ARL has been in service for 40 years during which time it has made many valuable contributions to the needs of the military services and the Australian aircraft industry, as well as to many diverse civil needs. All of the locally developed aircraft, targets and drones, guided missiles and free-fall weapons have been extensively tested in this tunnel and numerous investigations have been carried out on non-aeronautical subjects including funnel plumes, flow separations on ships' hulls, flows over airstrips and around buildings, road vehicles and wind generators. During the early sixties the tunnel performance was increased when a new power plant and fan of twice the original capacity were provided. In the seventies a digital data acquisition, recording and control system was installed to increase tunnel productivity and efficiency.

However, despite these improvements, the continuing demand for tests of expanding range and diversity has produced a growing need for a larger wind tunnel with improved flow quality. A salient factor has been the increased emphasis in recent years on support for Australian military air operations. Wind tunnel test requirements for such support, and for associated local design activities, include high angle of attack aerodynamics (combat manoeuvring), high lift aerodynamic systems for take-off and landing, helicopter aerodynamics and thrust vectored/augmented lift systems for V/STOL aircraft. Since such testing results in large blockage and/or downwash effects, the wind tunnel test section must be much larger than normal in relation to model size if corrections due to tunnel wall constraints are to be kept within acceptable limits. Moreover, complex high lift systems must be modelled with good fidelity, and this can be achieved only by using large models. These factors together with the requirement to keep the test Reynolds number as high as possible have generated a need for a larger tunnel.

Since large tunnels are expensive, alternatives should be considered. The alternatives are:

(a) To rely on overseas aircraft manufacturers for the aerodynamic data on purchased aircraft.
(b) To carry out tests in large overseas tunnels.
(c) To rely on flight testing using specially instrumented aircraft.
(d) To use computational fluid mechanics to estimate aerodynamic data required, or to supplement data from the existing low speed tunnel.

None of these alternatives is considered satisfactory for the following reasons.

Experience has shown that manufacturer's aerodynamic data are not always readily available or are not applicable to Australian operations. Data on the Mirage and F111, in particular, have not been adequate for mathematical modelling or operational problem-solving purposes, and supplementary data have had to be obtained from local facilities. Also, the first alternative makes no provision for obtaining data on Australian-designed aircraft.

Using overseas tunnels would be extremely costly and would have to be planned well in advance. Difficulties would be expected in even gaining access to the more effective tunnels overseas because of their known high workloads. The test schedule would be very rigid and severe constraints would exist in carrying out any extra investigations shown to be necessary.

In addition, security and communication problems are likely and the inflexible working arrangements would generally be unacceptable for research and development.

Flight testing is another possibility in view of the recent advances made in instrumentation, data acquisition systems and data analysis. Nevertheless, flight testing is much more expensive and usually less comprehensive than wind tunnel testing and relies on aircraft being available for long periods of time. Moreover, this approach cannot be used to obtain data in unstable or dangerous flight conditions, (e.g. tail off) and cannot be used to obtain initial design data.

Although great progress is being made in computational fluid mechanics, and numerical methods will, in the future, reduce the reliance on wind tunnels for aerodynamic information, it is not yet possible to represent adequately the complex flow fields occurring in practice and it is not expected that these methods will obviate the use of wind tunnels within the life of the currently proposed facility[1].

Some of these alternatives also make no adequate provision for non-aeronautical wind tunnel testing, an area which has been and will continue to be of considerable importance.

In view of the unsuitability of the possible alternatives it is considered necessary for Australia to acquire new low speed testing facilities to meet the direct needs of the defence forces and the aircraft and missile industry, as well as to provide for research and development in aeronautics and other fields.

Since a major new wind tunnel of considerable size and complexity would be expected to have a life of at least 30 years, and since the time required to design, build and commission such a tunnel would be of the order of 5 to 10 years, it is necessary to anticipate likely test requirements for up to 40 years ahead.

It is envisaged that the proposed new tunnel would be regarded as a national facility and be used not only for military aeronautical problems, but also for civil aeronautical problems as well as non-aeronautical and industrial aerodynamics. It should also be available to universities and industry in accordance with relevant priorities.

2. POTENTIAL FIELDS FOR AUSTRALIAN RESEARCH AND DEVELOPMENT IN LOW-SPEED AERODYNAMICS

The proposed new wind tunnel would provide greatly improved capabilities for a wide range of research and development work in low-speed aerodynamics in both the aeronautical and non-aeronautical fields. Before discussing tunnel performance requirements, the likely nature of the demands for its services should be considered. The following paragraphs list some areas of future work for which considerable demand is envisaged and for which the present wind tunnel capability is inadequate. Some more speculative tasks for which a future requirement may arise are also mentioned.

2.1 Aeronautical Aerodynamics

2.1.1 Military aircraft

Although the local aircraft industry currently is not in a position to design advanced combat aircraft, it does have the capability to produce such aircraft to overseas designs. Irrespective of the production source of combat aircraft operated by the Australian armed services, it will be necessary to have adequate local wind tunnel facilities to verify or complement overseas tests, to evaluate local design modifications, and to provide information relevant to local operational needs (such as the carriage of stores specific to Australian requirements). Test areas to be covered would include high angle of attack aerodynamics, separated vortex flows, the aerodynamics of high lift systems, airframe/engine exhaust flow interactions, and the carriage and release of stores. Most of these test areas require the testing of models at high angles of attack and/or the use of large models for accurate representation of surface detail at realistic Reynolds numbers. In either case, a larger tunnel than that currently available is required to avoid excessive tunnel interference effects and to ensure high quality results which can be extrapolated to flight conditions with some degree of confidence.

There is a strong possibility that Australia will operate V/STOL fighter aircraft in the future, initially to satisfy Naval requirements. The wind tunnel testing of such aircraft requires

the accurate representation of highly-deflected wakes and engine exhaust flows in free air and close to the ground. Current facilities do not allow tests of this nature.

The design and production of a military trainer or light transport aircraft is well within the present capability of the Australian aircraft industry. A wind tunnel program in support of the design and development of such aircraft is likely to be much more comprehensive than the type of program discussed above in relation to combat aircraft designed overseas. The only wind tunnel test results available would be those obtained locally, and these would be required for all stages of the design evolution. It is important that local tunnel facilities be capable of providing data sufficient in extent and quality to ensure that locally designed aircraft can fly safely and that performance and handling specifications can be met. A larger tunnel with substantially better flow quality than that currently available would be required for such work.

2.1.2 Civil aircraft

Although there is little current Australian production of light aircraft, as for military aircraft the local industry is technically capable of such work. Nomad provides evidence that local design and production of light transport aircraft is also feasible. As in the case of the military trainer the pre-flight design phase of such aircraft is considerably hindered by inability to predict real flight behaviour with a high degree of accuracy from model test data.

Australia is unlikely to produce large transport aircraft independently, but could become involved in cooperative ventures with overseas companies. Apart from immediate economic considerations, a particular advantage of undertaking such work is the opportunity for the acquisition of advanced overseas design data and industrial techniques. The availability of wind tunnel facilities in Australia suitable for the testing associated with this type of aircraft would be a useful asset in gaining participation in such cooperative projects.

The increasing density of air traffic in Australia, coupled with the growing number of wide-body aircraft, is likely to focus increasing attention on the hazards caused by aircraft vortex wakes. Studying this problem in a wind tunnel has the advantages of ease of model modification and controllability of test conditions, but necessitates an examination of the wake flow at a considerable distance behind the model. To do this with a model of reasonable size requires a tunnel with a longer working section than has been conventionally accepted.

Future research in civil aircraft aerodynamics will include the field of drag reduction. Pertinent areas of interest are the aerodynamics of winglets (for reduction of induced drag), laminar flow control (for reduction of skin friction drag) and airframe clean-up (for reduction of parasite and interference drag). Such investigations would require both a high quality basic flow and the availability of a large tunnel allowing the use of large models.

2.1.3 Helicopters

Helicopters are playing an increasingly important role in military and civil air operations. While helicopters are unlikely to be designed locally, it is necessary to have the capacity to undertake investigations into relevant operational problems. Such investigations would include, for example, the study of rotor aerodynamics and dynamics, performance, stability or control problems caused by local operational environments or equipment (including operations aboard ship and in mountainous terrain, and ASW operations); or the provision of data for the mathematical modelling of helicopter behaviour.

2.1.4 Missile and RPV aerodynamics

Australian industry and research organisations have considerable experience in missile and RPV design and development. To support the continuing requirement for local design and manufacture of such systems, accurate information on the aerodynamic characteristics of the missile or RPV must be provided. Such vehicles may be of unconventional shape, and may have to operate at extreme angles of attack. It is highly desirable to test full scale models in the wind tunnel without causing excessive blockage, at attitudes which may be very large.

2.2 Non-aeronautical Aerodynamics

2.2.1 Ships

The dispersion of exhaust plumes from ship funnels continues to be an important area of study by ARL, particularly for Naval vessels. The investigation of plume dispersion requires a model large enough to allow details of the superstructure, including uptakes and intakes, to be represented at a reasonable scale, for the flow to be simulated adequately. The working section of the existing ARL low-speed tunnel has proved to be rather small for this purpose.

The modelling of the flow patterns and turbulence levels in the vicinity of helicopter landing pads is also likely to be of continuing interest. Once again, the use of large models is necessary to allow the accurate representation of details of the ship superstructure and so that adequate details of the local flow may be distinguished.

Large models and high Reynolds numbers are important requirements in the wind tunnel study of the flow over the underwater portion of a ship hull. A considerable amount of work of this type has been requested in recent years from ARL. While a substantial degree of success has been achieved to date, extrapolation to full scale from the test Reynolds number obtainable at present is necessarily somewhat tentative, particularly for accurate prediction of operational economics.

2.2.2 Ground vehicles

With increasing emphasis on fuel efficiency of ground vehicles, both road and rail, the reduction of the aerodynamic drag of such vehicles has become increasingly important. Large models with representative surface detail, underbodies, intakes and exhausts, or actual vehicles are desirable for wind-tunnel testing.

Air cushion vehicles are particularly suitable for use in areas of varying and difficult terrain and coastal regions where road access is unavailable. Such vehicles are being used increasingly in other countries by military and civil operators, and it would seem probable that they will be adopted in Australia with its large areas of poor surface communications. A requirement for wind tunnel testing can be anticipated in connection with any local design, production or operation of air cushion vehicles. The large models desirable for ground vehicle investigations in turn require sufficiently large wind-tunnel test sections to accommodate them.

2.3 Additional Fields for Low-speed Aerodynamic Investigation

Tasks mentioned in this section must currently be considered rather speculative but a future requirement may well arise.

2.3.1 Airships

There is currently a revival of interest in airships because of their relative efficiency in moving bulky articles of freight to and from fairly simple landing sites. Their long endurance makes them also potentially useful as coastal surveillance platforms. As in the case of ship hulls, wind tunnel testing calls for the largest possible models to minimise scale effect.

2.3.2 Wind energy conversion systems

The use of wind energy in Australia in the future on a much larger scale than at present is a possibility already under intermittent consideration. Testing of practical models of the very large machines necessary for economic large-scale generation of electricity will require a large wind tunnel.

2.3.3 Terrain modelling and building aerodynamics

While, in general, such work is undertaken within their own precincts by universities, such as Monash, which have specialised in this field, security restrictions may require some investigations to be carried out in Government laboratories. Fields of interest may include the dispersal of gases and airborne particles over terrain; the effects of wind (including cyclones) on structures; and the effect of turbulence and wind shear over airports and helicopter landing pads.

2.3.4 Aerodynamic noise

The aerodynamic noise generated by aircraft, helicopters and wind generators is receiving considerable attention overseas, and consideration should be given to the possibility of a future requirement for acoustic testing.

2.3.5 Internal aerodynamics

The airflow through ducts such as those used in manufacturing processes and in airbreathing engines may call for the testing of large models or full-scale hardware.

3. REQUIREMENTS FOR WIND TUNNEL MODELLING OF FULL SCALE FLOWS

The accurate prediction of full scale flight behaviour from the results of wind tunnel tests requires the flow about the model in the tunnel to be closely similar to that which occurs at full scale in free flight. This requirement has become increasingly stringent because of the critical effects of boundary layer behaviour on the performance of modern aircraft[2].

In order to achieve adequate simulation in the tunnel many factors need to be considered such as model fidelity, scaling parameters, and the effects of tunnel boundary constraints. Moreover, the problems associated with these factors are greatly increased when a model is tested at large angles of attack or is fitted with a high lift system which produces a large downwash. Most, if not all, of these problems are alleviated substantially by increasing the size of the model and the test section, and the test Reynolds number. Where a large downwash is involved the test section size relative to that of the model must also be considerably greater than would otherwise be the case.

A low level of freestream turbulence and an adequate test Reynolds number, together with the faithful reproduction of model detail, are particularly important in achieving the correct surface flow over the model. If the Reynolds number is too low, flows in which viscous effects are important are not truly representative of their full scale counterparts. Thus the condition of the boundary layer and in particular the occurrence of transition and separation will be incorrectly represented. Because of the effects of Reynolds number on the boundary layer, a high test Reynolds number is essential for precise evaluation of drag. A high test Reynolds number is again necessary when simulating the flow over a wing operating at a high angle of attack near stall, for example, during combat manoeuvring and during take-off and landing, and for predicting the stall boundary accurately. Both Reynolds number and model fidelity are critically important in testing models with complex aerodynamic control surfaces, where small components and gaps, and the flow around and between them, must be accurately represented[3,4].

In an atmospheric wind tunnel, where the Reynolds number is directly related to model size and freestream velocity, a high Reynolds number should be obtained by using large models (which in turn require larger test sections) rather than by using higher freestream velocities which can introduce spurious Mach number effects. Obtaining higher Reynolds numbers by increasing model size also permits improvement in model fidelity.

In testing of V/STOL aircraft, helicopters and high-lift systems the problem of adequate model fidelity is magnified by the complexity of the aerodynamic outline. Moreover, the large downwash implicit in testing at such high lift invalidates the basic assumption underlying conventional wind-tunnel testing, namely that the flow leaving the trailing edge remains approximately streamwise. The use of conventional ratios of model size to tunnel size results in very high tunnel wall corrections which may vary considerably in both the streamwise and transverse directions. At best it may be impossible to assess the tail contribution correctly, and if the downwash strikes the floor beneath the model an upstream separation may result, producing a flow which is unrepresentative of free air conditions and which cannot be corrected to provide usable results. To overcome this problem with reasonably sized models, large test sections are obligatory especially for simulating flight at low forward speed. In general, the test section linear dimensions should be at least three times the model span (or rotor diameter) if the tunnel walls are solid and boundary corrections are to be kept within acceptable limits[5]. However,

in recent years attention has been given to the use of ventilated or flexible wall sections, which reduce tunnel boundary effects compared to solid fixed walls and alleviate, to some extent, the requirement for very large test sections, or permit larger models to be used in a test section of given size.

Although, in most cases, the final performance will not be known until the aircraft is actually flown and flight tested, the very large costs involved in developing new aircraft make it essential to obtain the best possible pre-flight data. This, in turn, requires the availability of a low-speed tunnel which can closely simulate flows which occur in real flight, and test models which accurately represent the full scale aircraft.

4. EXISTING AUSTRALIAN WIND TUNNELS

There are a number of relatively-small low-speed wind tunnels at various universities and technological institutes throughout Australia. While these tunnels are suitable for student use and for some basic research in fluid mechanics they are, in general, small and/or limited in speed range.

The test facility with the greatest capability for aircraft research and development in Australia at the present time is the low speed tunnel at ARL, first commissioned in 1941. It has an octagonal test section $2 \cdot 7$ m wide, $2 \cdot 1$ m high and $3 \cdot 6$ m long, and has a stable airspeed range from about 8 m/sec to 100 m/sec. Based on the commonly-accepted length scale of $0 \cdot 1(A)^{1/2}$ where A is the cross-sectional area of the test section, a maximum test Reynolds number of about $1 \cdot 6 \times 10^6$ can be achieved.

While limited basic research might be undertaken in the ARL tunnel on small V/STOL models, it is too small for work with direct application to specific aircraft of this type. In addition, for conventional aircraft the available test Reynolds number is too low to permit the prediction of performance to the accuracy now generally required.

However, although there is a requirement for a new low-speed wind tunnel of appreciably greater capability, it is considered very necessary to retain the existing $2 \cdot 7$ m $\times$ $2 \cdot 1$ m tunnel for the many tasks for which it is eminently useful, such as smaller development and ad hoc tasks. Its smaller size and less sophisticated back-up systems will render it more economic for such work.

5. CONSIDERATIONS FOR A WIND TUNNEL TESTING FACILITY FOR CURRENT AND FUTURE NEEDS

When considering a suitable test facility for investigating problems in the fields of interest outlined in section 2, it is necessary first to decide the type of circuit and test section best suited to the task, and the question of tunnel pressurisation.

5.1 Type of Circuit and Test Section

Open circuit tunnels are not, as is often assumed, inherently inefficient, as the energy lost at discharge is only a small proportion of the total. Pope and Harper[6] state that even with the greater number of screens to be expected in an open circuit tunnel power requirements should only be 10 to 15% higher than in one with a closed circuit.

Problems resulting in operating restrictions are, however, caused by outside weather conditions including gusts, rain and extremes of temperature. Birds, insects and dust may be troublesome. Since the test section operates at less than ambient pressure, the flow field is distorted by inflows around mounting pylons and other apertures.

While all of these problems can be coped with at least to a considerable extent, it is usually concluded that the extra expense incurred in building a closed circuit tunnel is more than offset by the gain in flow quality and stability, and convenience of operation.

For some test requirements, e.g. where operation of fuel burning engines is required, in some jettisoning tests, or where there is possibility of structural failure such as in testing structural elements designed to withstand cyclonic conditions, or in testing for rain penetration, an open circuit might be very useful, and it might be profitable to provide for appending an open-circuit leg to the main structure at some future date, as has been done in recent modifications to some American tunnels.

Comparison of closed with open test sections shows that, while solid and wake blockage corrections may be considerably smaller in an open test section[6], the closed section has advantages which include a substantially lower power requirement, higher quality airflow and quieter operation. For these latter reasons a closed test section is usual in general purpose wind tunnels and has been selected in the present case. The advantages of slotted or porous test sections are now becoming more widely recognised, and for this discussion they are considered as a special class of closed section with intermediate boundary conditions.

5.2 Tunnel Circuit Pressurisation

Spence and Spee[7] estimated that pressuring a tunnel to 2 or 3 atmospheres would increase capital costs by a factor of about 4 compared with an unpressurised tunnel of the same size.

On the other hand, if attainment of a given maximum Reynolds number is the overriding aim, their data show that a pressurised tunnel would be cheaper both in capital cost and running cost than a sufficiently-large atmospheric tunnel, and they state that the smaller models used are likely to be cheaper and quicker to make even allowing for the higher loading. Additionally, varying the pressure would enable a range of Reynolds number to be obtained for a given Mach number, assisting in extrapolation towards full scale in cases where scale effect can be expected to behave predictably. The smaller tunnel working section however, would limit the range of full scale hardware which could be tested and the use of smaller models would restrict the modelling of detail, the importance of which is stressed in section 3.

If a further comparison is made, on the basis of the same first cost, between a tunnel operating at 3 atmospheres and a larger atmospheric tunnel, data from Ref. 7 imply that the pressurised tunnel would permit an increase in Reynolds number of about 60%. However, for a pressurised tunnel of economically-acceptable size the higher Reynolds number would generally remain below flight values, and its worth must be assessed against factors such as model access and other difficulties of working with a pressurised environment, together with the problems of reduced model size mentioned above.

Overall, we feel, and it seems to be largely endorsed by practice overseas, that the advantages offered by an atmospheric tunnel outweigh the limited gains in performance of a pressurised facility.

5.3 Tunnel Size and Layout

5.3.1 Model size

As a first step in specifying the size of a new wind tunnel, the maximum size of model likely to be tested in it must be estimated. The minimum permissible size of working section is obviously closely controlled by the maximum model size, and by the flow pattern around the model. In deciding the appropriate size of model, various and sometimes conflicting requirements must be considered.

The model must be large enough for adequate detail to be correctly represented. In the case of a rotor the blade Reynolds number must be sufficiently high, the advance ratio correctly reproduced, and spurious Mach number effects avoided. The rotor dynamic behaviour must also be sufficiently close to full scale if operational behaviour is to be accurately assessed.

However large models are expensive and time-consuming to design and build, and to modify, and are difficult to handle. The large forces required to restrain them lead to massive mounting pylons with associated flow interference, and to large wind tunnel balances which require appropriate calibration facilities.

To design and build a fully representative large scale model of a lifting rotor system would generally be extremely expensive, and may cost more than the full scale production rotor itself. A very large facility would also be required which would be beyond the resources of most Western countries, probably even of the pooled resources of the EEC, and certainly could not be economically justified in Australia.

Templin[8] in discussion of the factors which prompted the Canadian decision to build a 30 ft (9·1 m) square tunnel, concluded that a wing span or rotor diameter of about 10 ft (3·0 m)

is required for adequate testing of industrial V/STOL models, and to obtain sufficiently high wing and rotor blade Reynolds numbers even greater spans may be required for STOL models with more than two propellers and with wings projecting well beyond the propeller slipstreams. The requirements for research models may be less stringent.

It seems appropriate in our own case to limit consideration to 1/3rd to 1/6th scale rotors which can produce useful background information for general design, investigation of operational problems, and for validating mathematical model studies. On this basis a maximum allowable rotor diameter of 3 m would cater for most foreseeable projects. This accords with the Canadian conclusion that it is necessary to be able to test rotors up to 10 ft (3 m) diameter.

In the case of models of conventional aircraft a wing span also in the vicinity of 3 m would allow control surfaces and other necessary details to be represented reasonably well so that force and moment increments, produced either on actuation of controls or when small changes are made to the configuration, are sufficiently large to be measured accurately. Models much larger than this would be more difficult to handle and probably prohibitively expensive.

5.3.2 Test section considerations

A facility of the size and power required for V/STOL work would be a major and costly undertaking and should retain, and preferably augment, the versatility which has made the present low speed tunnel a valuable piece of equipment from 1941 to the present time. While provision of an adequate V/STOL capability is an essential requirement of the new facility, the requirements for tests on conventional aircraft and missiles should not be overlooked. For models of a given maximum size tested under V/STOL conditions provision of a sufficiently-large working section will generally be the dominant requirement, while under conventional testing conditions a smaller working section would be adequate but a higher wind speed would be called for. Accepting that there would be some penalty from a reduction in overall circuit efficiency and an increase in length, it seems, nevertheless, that a tandem arrangement with a large low-speed working section followed by a smaller higher-speed working section downstream would provide a very versatile and technically-profitable arrangement.

The relative virtues of a tandem arrangement or a scheme of interchangeable working sections, contractions and diffuser fairings are discussed by Ewald[8]. He concludes: "If the emphasis is put on simple and reliable construction, high productivity, low investment costs, low maintenance costs, minimum technical risk and if the small section work load is at least equal or higher than the large section workload, the decision is clearly the tandem layout.

"If the emphasis is more on the side of large test section use, very high maximum speed in the large test section and if one accepts larger investment costs and lower productivity the decision tends towards the exchangeable test section layout".

Within DSTO, although there is a substantial requirement for a V/STOL testing capability there is at least an equal requirement for an improved conventional testing capability, so that the tandem arrangement appears to be the appropriate choice.

5.3.3 Test section size and shape

Taking the capacity to accept a 3 m diameter rotor as a design criterion for the larger test section, then if solid walls are envisaged and the boundary corrections are to be kept within manageable limits, (i.e. $\Delta\alpha$ not to exceed 10° and correction to tunnel dynamic pressure to be not greater than 10%) Ref. 5 suggests that a cross-sectional area of about 80 m³ is required.

Figure 7 of Ref. 5 shows that for a model of fixed span in a rectangular tunnel of given area, least correction to α is incurred at the lower end of the speed range when the major axis is vertical, and at higher speeds when the major axis is horizontal. A square section, while less than optimum at either end of the range, appears to provide a good compromise overall.

To test a 3 m diameter rotor a solid-walled test section would require a cross-section about 9 m × 9 m. When provided with a settling chamber of several times the test section area the resultant facility in terms of height and ground area would be rather massive. However, it is

felt that it should be possible to devise a ventilated-wall system which would enable models of the same overall size to be accommodated in a much smaller working, section say 6 m × 6 m. The problem of producing a variable system of slots or distribution of porosity which will minimise boundary corrections sufficiently for a wide selection of models remains to be solved but, nevertheless, considerations of the prime cost of very large structures and the space needed to site them, may well dictate that an Australian proposal should be based on the assumption that an adequate ventilated system would be developed. Furthermore, assuming even a moderate contraction ratio, larger models or even small full-scale aircraft could be tested in the settling chamber if the circuit were carefully designed and if a reduced quality of flow could be accepted for such tests.

Tests by Rae[9] have shown that corner fillets are undesirable in a test section to be used for V/STOL work. At large downwash angles the fillets tend to promote the forward migration of the wake flow up the wall and to precipitate earlier flow breakdown on the floor.

When testing under conventional lifting conditions minimum correction to α is obtained with a test section width/height ratio of 2 (Ref. 10). This ratio is not critical, however, and values between 1 and 2 produce little increase in $\Delta\alpha$. When power and speed requirements are matched for test sections in tandem an area ratio of about 2·25 appears to be of appropriate order, and suggests that a small section of about 4·7 m × 3·4 m would be near the optimum to combine with a large section of 6 m × 6 m. The small section would cater for a large variety of work on full scale components and models even exceeding 3 m in span at the higher-speed lower-specific-lift end of the test range.

In the case of a tandem arrangement the length of each working section should be sufficient for model nose and tail surfaces to be unaffected by flow disturbances emanating from the upstream and downstream contractions for the large section, and from the second contraction and the entry to the first diffuser for the smaller section. Ewald[8] found that for a square tunnel with a first contraction ratio of 4·9 and a rear contraction ratio of 2·5 the required length/width ratio was approximately 2·2 for the large test section and 2·0 for the smaller section. In the present case a test section length of 13·5 m for the large section and 10 m for the smaller would seem appropriate. To minimise the disturbances Ewald also found it necessary to extend the contractions.

5.3.4 Speed range and power requirement

While ideally, V/STOL models should be tested at forward speeds which diminish to zero, in practice tunnel wall interference resulting from the extremely-high downwash imposes a lower limit to test speed. For adequate investigation of stability and performance of lightly-loaded STOL aircraft and helicopters in the low speed flight regime, test data are required at speeds down to about 10 m/sec (Ref. 5). For some types of wind tunnel test, including non-aeronautical work an even lower speed may well be desirable if it is possible to retain sufficient accuracy of both control and measurement of speed. Designing for 10 m/sec in the small section would, in fact, provide a lower limit of less than 5 m/sec in the large section.

A balance between possible gains in accuracy in simulating full-scale flows and the rapid increase in power required as speed increases, suggests that upper limits of 60 m/sec in the large section and correspondingly 135 m/sec in the smaller section would provide a substantial testing capability for a relatively moderate power requirement of about 5·6 MW if the tunnel circuit is carefully designed.

5.3.5 Quality of flow and selection of contraction ratio

It must be stressed that the quality of flow in the test section may be quite as important as correct scaling. The need for accurate drag measurement throughout the lift range, and for accurate measurement of general force and moment components under conditions of high lift with imminent or partial separation, requires similar boundary-layer development at model scale as at full scale to ensure that transition, and then separation, follows an identical pattern. Major requirements are that the model scale Reynolds number is sufficiently high, that full-scale

surface conditions are adequately represented, and that the free stream is highly uniform in speed and direction with a minimal level of turbulence. Distortion of the flow by the test section boundaries must not alter the pressure distribution on the model to a greater extent than can be confidently predicted by theoretical methods of corre ·ion.

An adequate contraction ratio is mandatory to meet the requirement for uniform flow with a low turbulence level. There appears to be some uncertainty, however, as to what may be accepted as a sufficiently low level of turbulence. Bradshaw and Pankhurst[11] consider that a v-component r.m.s. intensity of 0·05% in the working section should be low enough for most purposes: they take a value of 5% as typical upstream of the screens, estimate that 5 or 6 screens of K = 2 will reduce this value to 0·2% in the settling chamber, and that a contraction ratio of 12 will then be required to give 0·05% in the working section.

Reference 11 also refers to results of Schubauer and Skramstadt which showed in a particular case that reduction of intensity below 0·1% had no further effect on transition. It was questioned, however, whether this result could be generalised and whether, in addition, there may have been some undisclosed special circumstance.

Green[2] concludes that while "effective Reynolds number" cannot be determined until the influence of tunnel turbulence is better understood, in any new tunnel intended for measurement of Reynolds number effects the free stream turbulence level must be low. He points out that, for uncertainty in effective Reynolds number to be less than 5%, a free-stream turbulence intensity in the longitudinal component less than 0·1% may be required. At the same time he refers to an argument in correspondence from Bradshaw in warning that the precise influence of very low turbulence remains in doubt.

Since the v-component after contraction is greater than the u-component, we accept, then, that in the light of present knowledge, a v-component intensity between 0·05% and 0·1% appears to be adequate. If we assume that the value of 0·2% estimated in Ref. 11 will be obtained in the settling chamber, then the contraction ratio required varies from 12 for the former value to 3 for the latter, using the expression $(\bar{v}_2^2)^{1/2}/(\bar{v}_1^2)^{1/2} = (3c)^{1/2}/2$ and dividing by c for the % intensity (c is the contraction ratio).

We conclude that a contraction ratio of 12 cannot be justified for the large test section on grounds of space requirements and structural expense, particularly in view of the uncertainty in interpretation of the effects of very-low turbulence. On the other hand, since the power required varies in inverse relation to the contraction ratio, selection of a contraction ratio of 3, while possibly providing insufficient margin for error in flow quality might also result in excessive running costs. A contraction ratio of about 6 appears to be an appropriate compromise.

In considering mean flow deviations Ref. 8 defines as undisturbed a flow having less than ±0·1% velocity variation at the centre line and less than ±0·2% at the walls, while Bradshaw and Pankhurst[11] consider that a velocity variation of ±0·2% and angularity within 0·1° are acceptable for a high performance tunnel. In general, these conditions will be met automatically by a flow with the proposed turbulence limit.

5.3.6 Diffusers

The overall extent of a wind tunnel circuit can be appreciably reduced by the incorporation of a wide-angle diffuser immediately upstream of the settling chamber. The effect of total tunnel-circuit energy losses on operational costs must be compared with design structural costs to determine whether such installation would be economical. Reference 12 asserts that satisfactory flow can be maintained in a 45° equivalent cone with an area ratio of 4:1 with 3 screens fitted. Reference 11 advocates a 2:1 sudden expansion before a 12:1 contraction.

From a literature survey Ewald[8] concludes that attached flow with a good velocity distribution can be obtained with a screen of resistance coefficient $K = (F_2/F_1)^2 - 1$ where F_1 and F_2 are the cross-sectional areas at the beginning of the diffuser and at the screen. He considers that it is preferable to include several screens, the area ratio of each part not to exceed 1·3 or 1·4. Normally two screens are called for, one in the middle and one at the end of the diffuser. Ewald claims that the resulting flow is better than that at the same location in a normal wind-tunnel circuit. The second screen may be replaced with a water cooler/honeycomb of the same resistance.

It is considered that a 5° diffusion angle from the working section to the second corner, followed by a 6° diffusion angle to the final diffuser should ensure acceptable conditions at entry to the working section.

6. OTHER CONSIDERATIONS

While the requirement for building a major low-speed tunnel has been stated, and a proposal for a circuit layout described, there are many other matters which would need to be resolved but which it is not appropriate to discuss in detail at this stage. These include power plant and speed control, powering of auxiliaries, provision of a moving belt or floor-boundary-layer control system, tunnel instrumentation, model control, and data acquisition and processing.

7. LARGE OVERSEAS WIND TUNNELS

Table 1 enables the present proposal to be compared with some large tunnels in operation overseas. The table is based on Table 2 of Ref. 13 somewhat expanded and brought up to date.

TABLE 1

Tunnel	Test Section Size (m)	Max. Speed (m/sec)	Drive Power (MW)
NAE 30 ft., Ottawa	9·1 × 9·1	61	7·5
Low Speed, Lockheed-Georgia Co. Marietta, Georgia	7·9 × 9·1 7·0 × 4·9	56 123	6·7
V/STOL, Boeing Vertol, Philadelphia	6·1 × 6·1 closed, open, and slotted	134	11·2
V/STOL Transition Research Tunnel, NASA, Langley Field, Va.	4·4 × 6·6	103	6
5 m Tunnel, R. A. E. Farnborough	5·0 × 4·2 (pressurised)	109	8
F-1, ONERA, Toulouse	4·3 × 3·5 (pressurised)	120	8·8
DNW, German Dutch tunnel, Noordoostpolder	9·5 × 9·5 closed and slotted; 8·0 × 6·0 closed, open, and slotted; 6·0 × 6·0 closed and slotted	62 110 145	12·7
Full Scale Tunnel NASA Ames, Ca.	12 × 24 closed 24 × 37 open	150	100
ARL (proposed)	6 × 6 slotted, 4·7 × 3·4 closed and slotted	60 135	5·6

8. CONCLUSION

The accurate prediction through wind-tunnel testing of the performance of modern aircraft requires large models to permit adequate reproduction of details affecting the surface flow and to achieve Reynolds numbers allowing representative boundary layer states to develop. In general rotor diameters or wing spans of about 3 m are necessary.

Testing of models of this size under STOL conditions requires a test cross-section of about 9 m × 9 m if the test section walls are solid. It may be possible to reduce the test section size to about 6 m × 6 m by providing appropriate ventilation of the walls.

A 6 m × 6 m ventilated section could readily be allied with a section, say 4·7 m × 3·4 m, in tandem, allowing testing of similar sized models at higher speeds under conventional lifting conditions, the power requirements remaining moderate. It would be less easy to match a high speed section suitably to a 9 m × 9 m section for the same velocity in the large section and the same overall model size, and the power requirement would be appreciably greater.

For a new wind tunnel to have the capability to provide aerodynamic data of the accuracy necessary in the forseeable future a ventilated test cross-section of 6 m × 6 m is considered the minimum feasible, and more detailed consideration may indicate that a somewhat larger section should be specified.

An outline for a tunnel with tandem sections of the sizes discussed is shown in Fig. 1, and for comparison Fig. 2 shows the Canadian 9·1 m × 9·1 m tunnel, Fig. 3 the Boeing 6 m × 6 m tunnel and Fig. 4 the Lockheed-Georgia tunnel.

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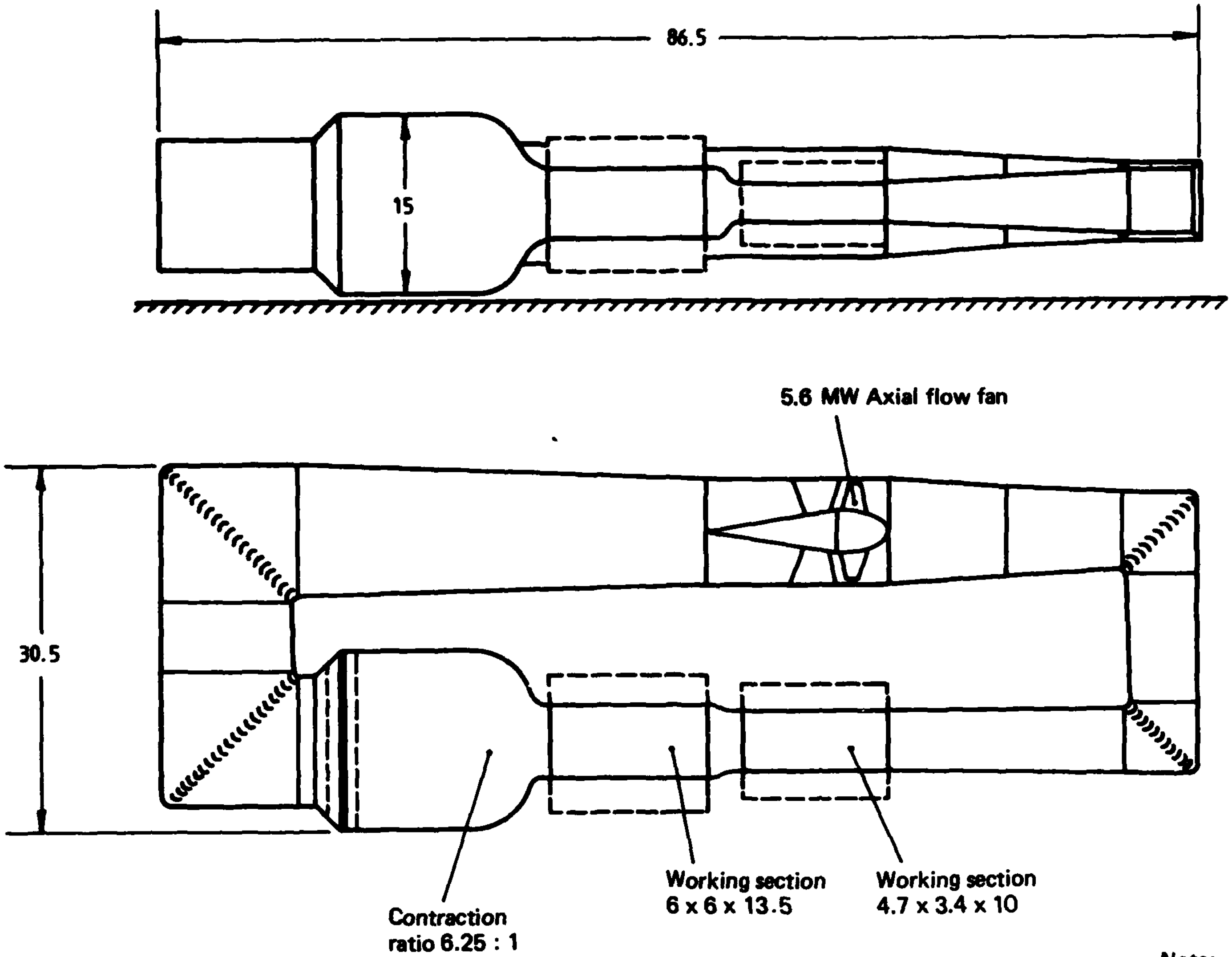
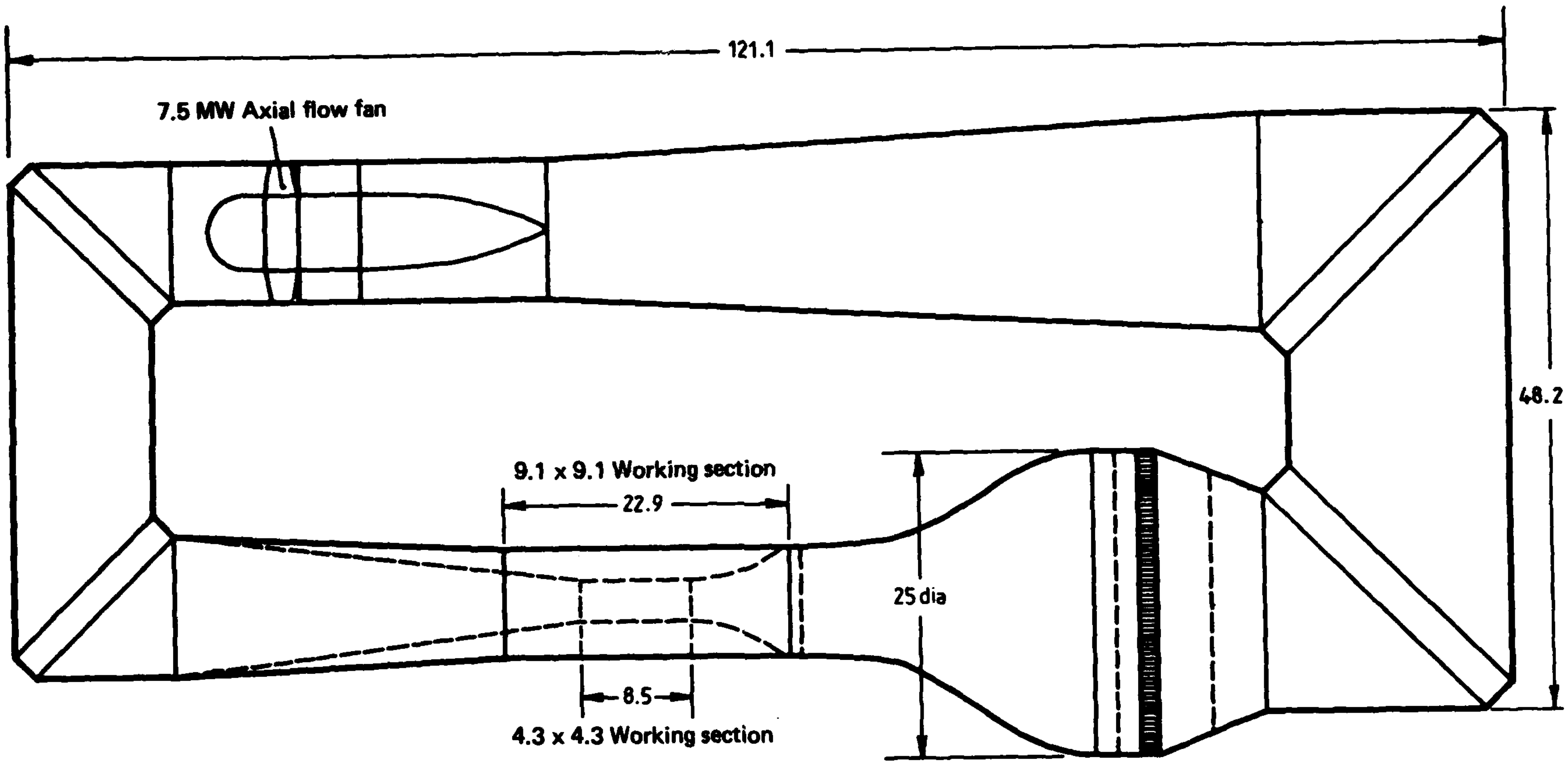


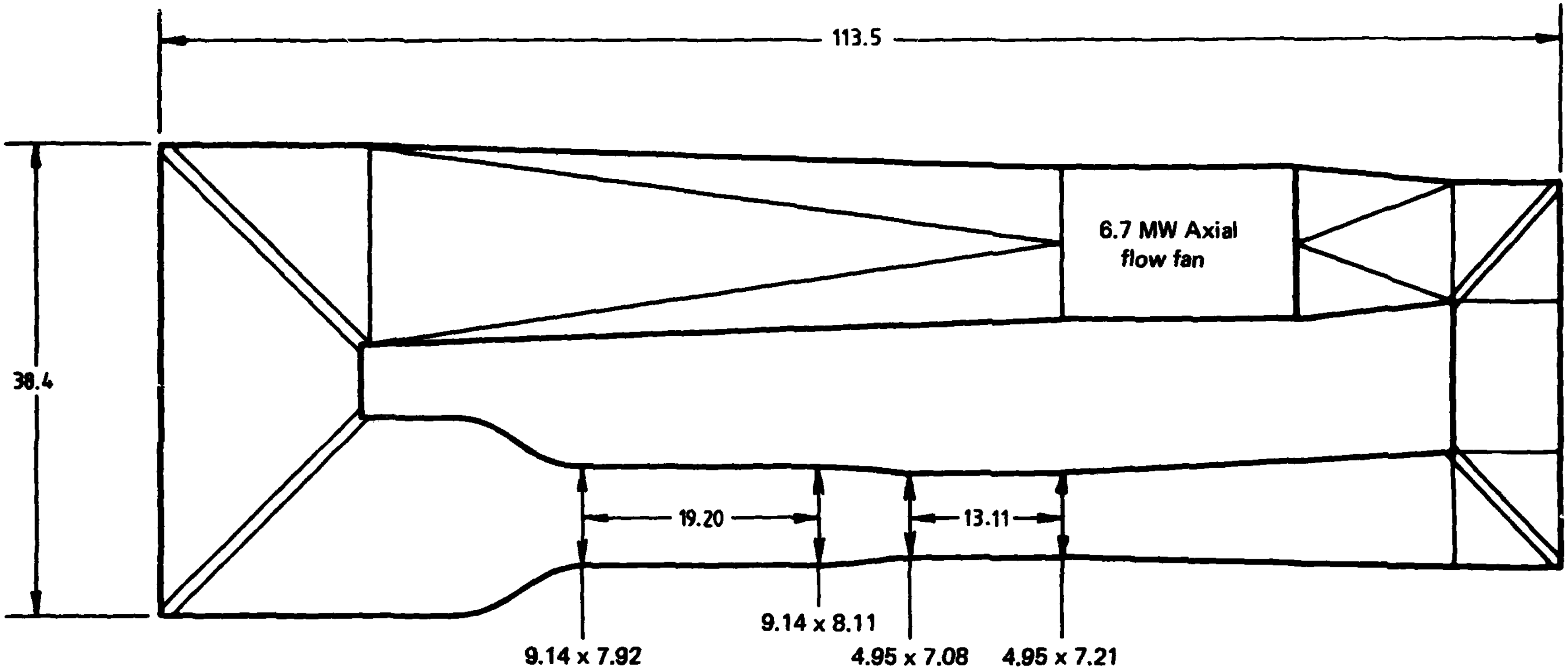
Note: Scale 1 : 500
Dimensions in metres

FIG. 1 SCHEMATIC OUTLINE OF PROPOSED ARL WIND TUNNEL CIRCUIT
PRESSURE – ATMOSPHERIC



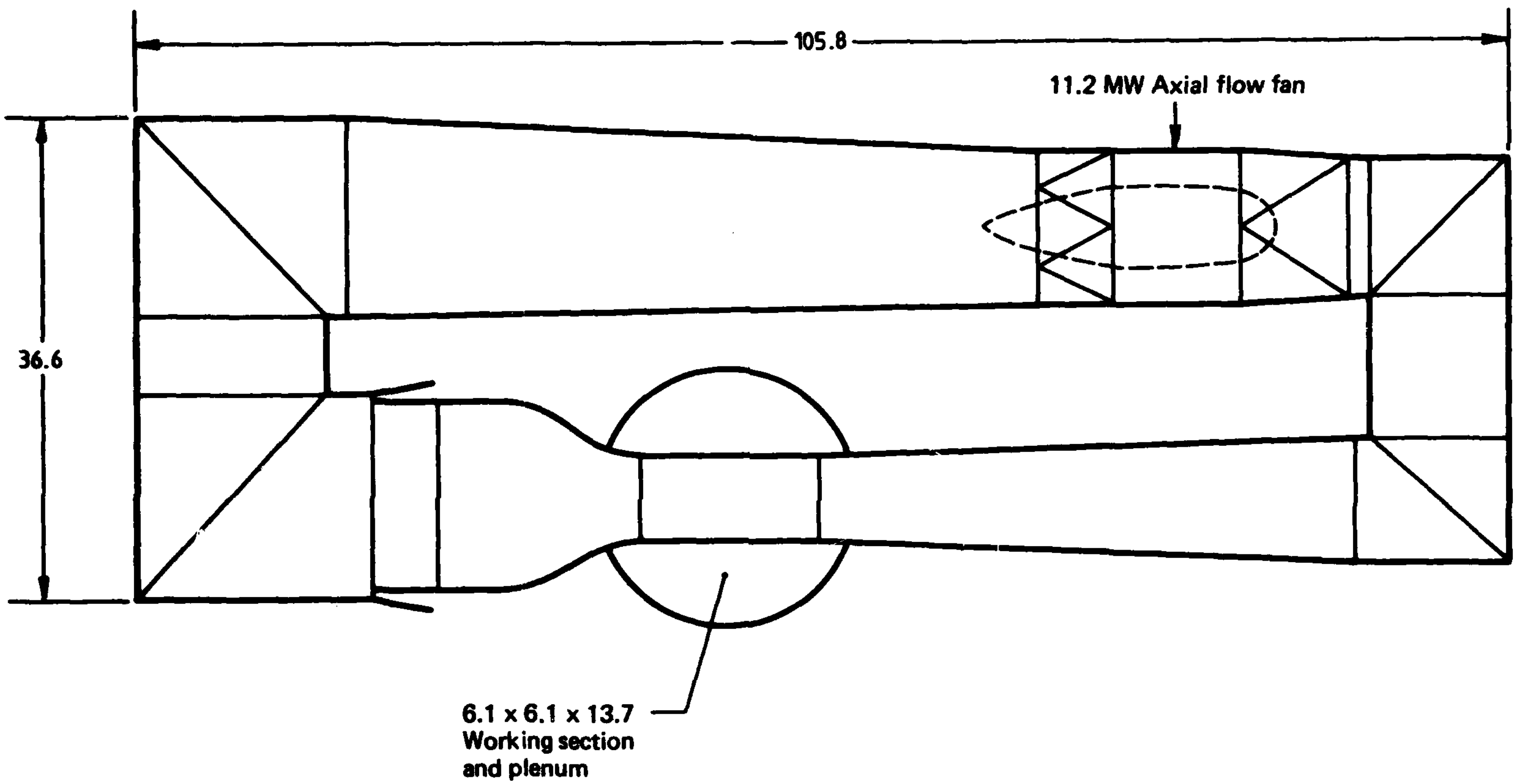
Note: Scale – 1 : 500
Dimensions in metres
Contraction ratio 6 : 1
Pressure – atmospheric

FIG. 2 CANADIAN 9.1 m x 9.1 m WIND TUNNEL CIRCUIT



Note: Scale – 1 : 500
Dimensions in metres
Pressure – atmospheric
Cross-section dimensions = height x width

FIG. 3 LOCKHEED – GEORGIA WIND TUNNEL CIRCUIT



Note Scale – 1 : 500
Dimensions in metres
Pressure – atmospheric
Contraction ratio 6 : 1

FIG. 4 BOEING, VERTOL DIVISION, WIND TUNNEL CIRCUIT

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